Introduction to the world of RF; Transmission Lines, Impedance Transformers, and RF Components

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Introduction:

Talk divided into four parts:

1. Transmission Lines and Circuit Theory
2. Impedance Transformation Techniques
3. Practical considerations of RF components including coaxial cable, capacitors, inductors, and resistors.
4. Useful circuit components including lumped element equivalent of transmission lines, phase shifters, and power combiners/splitters

Part I: Transmission Lines and Circuit Theory [1,2,3,4,5,6]:

A. General Importance:
    1. Transmission lines fundamental component of any RF system
    2. Allow signal propagation and power transfer between scanner RF components
    3. Basis for RF circuit theory and design

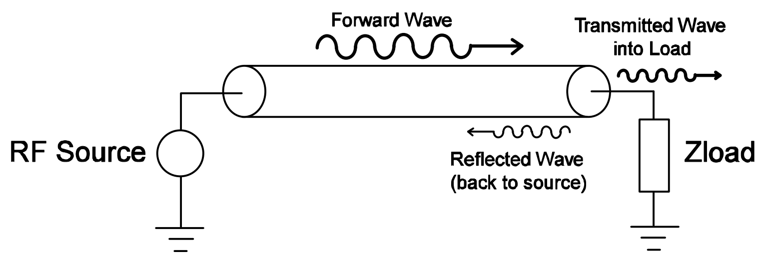
B. Characteristic Impedance:
    1. All lines have characteristic impedance (ratio of voltage/current)
    2. Z0 = (L per unit length/ C per unit length) ^ 0.5
    3. Range from ten to few hundred ohms
    4. RF design for MRI almost always makes use of Z0 = 50ohm

C. Wave Velocity:
    1. Propagation velocity = (L per unit length * C per unit length) ^ (-0.5)
    2. Typically ranges (relative to speed of light) from 1 (air filled lines), 0.7 (plastic filled lines), to 0.1 special microwave substrates.
    3. Input and output of transmission line have a phase difference corresponding to time it takes wave to go from one end to other end.
    4. Length of line is often referred to according to number of wavelengths at a given frequency (e.g. a half wave or $\lambda/2$ cable)

D. Geometry:
    1. Coaxial: Most commonly used transmission line.
        a. Characteristic Impedance [4] : Z0 = 138 * log (b/a) / sqrt(ε_r) where b=outer conductor radius, a =inner conductor radius, ε_r=relative permittivity of material between inner and outer conductors.

2. Twin Line: Rarely used though can arise unintentionally between outer conductors of coaxial cable, typically higher impedance than coaxial line.
3. Microstrip: Flat conductor over ground plane.
    a. Models conductors on flat PC boards with ground plane
    b. Consult references or for approximate formulae [2,3,4]
    c. 115 mil (3mm) wide copper strip on 62mil (1.6 mm or 1/16" inch) thick G10 (or FR4) PC board is approximately 50 ohms.

E. Line reflections:
1. Consider situation where a wave generated by a RF source is traveling down a transmission line of characteristic impedance Z0 that ends in a load of impedance Zload. This termination impedance may be a resistor, RF coil, preamplifier, or another transmission line(s). In general, there will be reflected and transmitted waves at the load:



2. At load we have:
    a. Forward Wave (forward power) = P_i
    b. Reflected wave (reflected power) = $P_i * (Z_{load}-Z_0) / (Z_{load}+Z_0)$
    c. Transmitted wave (transmitted power) = $P_i * 2Z_{load}/ (Z_{load}+Z_0)$
    d. Unless $Z_{load} = Z_0$, then there will be a reflected wave backwards along line. This leads to the formation of standing waves along cable.

3. Can define commonly used relations:
    a. Reflection coefficient = fraction reflected power =
    $\Gamma = (Z_{load}-Z_0)/(Z_{load}+Z_0)$

    b. Transmission coefficient. = fraction transmitted power =
    $T = 2Z_{load}/(Z_{load}+Z_0)$

    c. Often use "s parameters" to refer to reflected and forward waves:
    S_{11}= reflected power = Γ
    S_{21}= transmitted power = T

    d. Impedance seen at point distance L away from load (as measured in wavelengths along line of characteristic impedance Z0):
    $Z_{in}=Z_0 * (Z_{load} + j*Z_0*\tan(2\pi*L))/ (Z_0 + j*Z0*\tan(2\pi*L))$

e. Voltage Standing Wave Ratio (VSWR) = $(1+|\Gamma|)/(1-|\Gamma|)$

f. Smith Chart Transformation [4,5,6]: A useful tool for making quick transmission line and matching calculations graphically. Charts and several programs are available which make use of the smith chart (see software below).

4. At RF frequencies, devices are described by reflection and transmission coefficients (S parameters)
   a. Different than at low frequencies where voltage gain, impedance are used to describe circuit elements
   b. At high frequencies use measurement of forward and reflected power since:
      1. High frequencies, parasitic reactances (1" 20AWG wire is approximately 20nh = 35ohms at 300mhz) affect measurement making direct "voltmeter" readings of voltage, current, and impedance difficult
      2. Some active devices will not be stable unless resistively terminated
      3. All available measurement equipment is calibrated in terms of these parameters
   c. If desired, can convert S11 to impedance (R + jX ohms) using equations, smith chart, or software.
   d. Modern network analyzer can directly compute impedance at arbitrary point along transmission line by compensating for the "electrical delay" of the line.

5. Effects of high reflection coefficients (e.g. poor "matching" or transfer of power to a load impedance)
   a. High Power Applications (e.g. power amplifiers, transmit/receive coils, body coils):
      1. High Reflection coefficient decreases power transfer to a load consequently causing loss of expensive RF power.
      2. High reflection coefficients increase line loss: 3dB power loss can increase to >9db with a severely mismatched load [6].
      3. High reflection causes standing waves and increased voltage or current at specific locations along the transmission line.
   b. Low power:
      1. Low reflection coefficients often less important
      2. High reflection coefficients can cause instability in active devices, changes in frequency response of system, and other undesirable component interactions.
      3. In some cases, reflections can be used to good advantage e.g. high reflection coefficient preamplifiers can be used to "detune" a receive-only coil array.

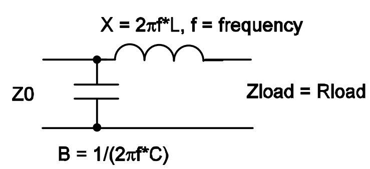
6. Useful transmission line facts to remember (derived from 4c above):
    a. Reflected wave = 0 for lines terminated with their characteristic impedance.
    b. lambda/4 line (or odd multiples thereof)
        1. Short one end => open other end
        2. Can be considered resonant structure with high current at shorted end and high voltage at open end.
    c. lambda/2 line (or multiples thereof)
        1. Impedance at one end => same impedance at other end e.g. short one end => short at other end.
        2. With opens at both ends, this also can be considered a resonant structure with high current at center and high voltage at ends.

Part II. Impedance Transformation[1,2,3,4,5]:

A. Given importance of reflections: generally desirable to match a given device to characteristic impedance of cable.

B. Can use broadband or narrowband matching circuits. Most MRI systems operate over limited bandwidth (<1mhz) so narrow band circuits work fine for passive devices such as RF coils.

C. Multiple different circuits, a few of which are shown below:
    1. L network [3,4,5]

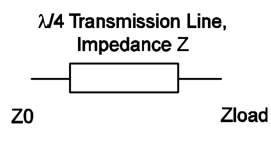


for Z0 > Rload:
X = sqrt (Rload * (Rload - Z0))
B = sqrt ((Z0 - Rload) / Rload) / Z0

Can swap C and L if:
X = (1/2πf*C) and B = (2πf*L)

Reverse network if Zin > Z0

    2. Transmission Line Transformer[1,2]:

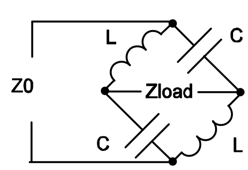


Z = sqrt (Z0 * Zload),

likewise Z0 = sqrt((Z ^ 2) / Zload),

can use multiple sections for increased bandwidth

    3. Bridge Balun [1]



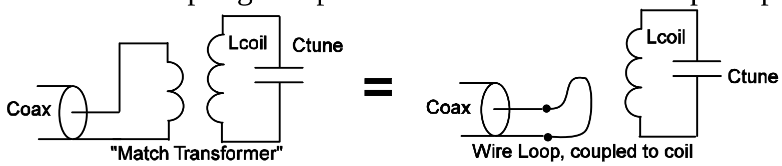
L = sqrt (Z0 * Zload) / 2πf,

C = 1/ (2πf * sqrt (Z0 * Zload))

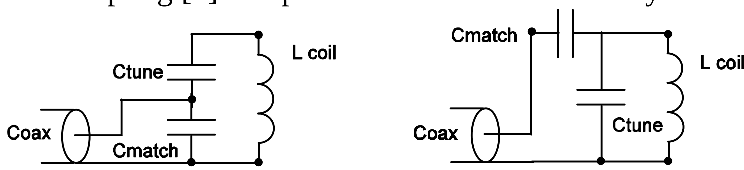
where f = frequency

Also provided balanced to unbalanced coversion (balun)

4. Inductive Coupling: simple coil match method with “pickup loop”



5. Capacitive Coupling [1]: simple and can match almost any desired RF coil



D. Typical coils might have impedance = 2 +100j ohms. Use capacitor(s) to “tune out” inductive reactance (e.g. tuning) and impedance transformation to covert resistance to 50 ohms. “Tuning and Matching” of RF coils basically corresponds to converting (e.g. matching) highly inductive coil impedance to 50 ohms.

III. Practical considerations of RF components:

A. Coaxial Cable and other transmission lines [6]:

1. Characteristic Impedance: almost always 50 ohms.
2. Wave Velocity: typically 0.7c for typical cable, higher with foam or air filled lines
3. Attenuation:
   a. Depends upon geometry, size, length of line, and frequency. Shorter cable, larger diameter, lower frequencies = lower losses
   b. Loss generally measured for matched loads. Ranges from 5-30db/100feet at typical frequencies
   c. For high power, lossy line waste expensive RF power, heats up (even melt) if overloaded.
   d. Important in that the MR signal is expensive and losses between receive coils and preamplifiers add directly to overall noise of system.
4. Non-matched loads have increased losses (e.g. low impedance preamplifiers, poorly tuned coils, etc). Power loss can be severe on mismatched lines.
5. Mechanical: Flexibility, size, strength.
6. Power Handling
   a. Voltage breakdown: typically ranges from 500V –5000V
   b. Average Power Handling- generally not a major issue with MRI since RF power is applied in pulses
7. Typical examples include RG-58, RG-316 (caution: often magnetic); RG-8 and larger cable for high power.
8. Connectors: BNC, SMA, SMB commonly used; N or other types for higher power.

9. Common Mode Current:
    1. All circuitry described parts I and II consider RF currents flowing on ***inside*** of cable: Even perfectly shielded cables appear on the ***outside*** as conductor capable of carrying current and voltage in unintended and often undesirable ways.
    2. Several Common Situations:
        a. coaxial cable bundle inside shielded magnet bore – effectively high impedance coaxial cable capable of carrying noise and RF power inside magnet bore
        b. two ?/4 lines shorted at one end, depending upon geometry can be resonant and couple strongly to body transmit coils.
        c. ??2 line in circular loop with ends close together – can also form self-resonant structure. Can pick up very substantial power from body transmitters.
    3. Baluns, cable traps of various sorts are commonly used to reduce common mode current the outside of coaxial cables.

    IMPORTANT: In addition to baluns, it is always good idea to put some sort of covering over cables which can come in contact with a subject. This reduces proximity of subject to potentially intense E and B fields along outside of coaxial cables. Most common cause of RF injuries in MR scanners are burns in receive coils occur with direct placement of cable (or coil conductor) directly against skin.

B. Capacitors[7]:
    1. Capacitive Reactance = X_c= 1 / (j2?fC), where f = frequency, C = capacitance
    2. Multiple different types and dielectrics: typical MRI applications use almost exclusively ceramic nonmagnetic components or variable capacitors with air or teflon dielectrics.
    3. Use of radio receiver type “ceramic disk” caps is generally discouraged - these are often magnetic, have excessive losses, and suffer from effects of lead inductance.
    4. Capacitance: typically ranges from 1-1000pf depending upon frequency
    5. Voltage breakdown can be an important characteristic: 50, 250, 500, 2500V and 3600V common values.
    6. Temperature coefficient
    7. Self-resonance effects: All capacitors have some series inductance which will resonant with capacitor at high enough frequency.
    8. High quality capacitors have lower losses than other typical components used.

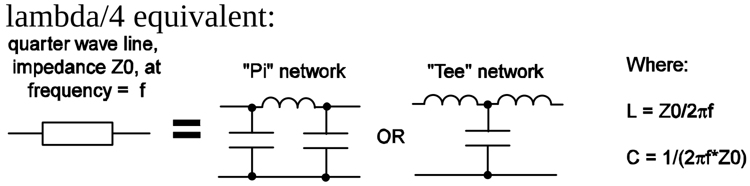
C. Inductors[7]:
    1. Inductive Reactance = X_l = j2?f L, where f = frequency, L = inductance
    2. Any wire with field has associated inductance

3. MRI "coils" consist of flat or curved single loop of low inductance wire or PC board.
4. For other inductors associated with MR scanners, frequently use hand or machine wound air core inductors though chip inductors are available when small size is required.
5. Inductance values: typically use several nanohenries (nh) to several microhenries (uh)
6. Generally component Q (= $X_{inductor}$ / $R_{indunctor}$) ranges from 25 (small chip inductor) to 400 large handwound coil
7. Self-resonant phenomenon: at high enough frequency any inductor will eventually appear as a capacitor.
8. Extensive inductance formulas can be found in [8]

D. Resistors / Attenuators [7]:
1. Surface Mount Chips work generally well. High power RF versions are available
2. Typical leaded resistors have significant inductance at higher frequencies, wire-wound resistors have particularly high series inductance.
3. Attenuators reduce signal levels and reduce reflections between components. High power versions available in connectorized and chip form.

Part IV. Useful Circuit Elements:

A. Lumped Element Equivalent of Transmission Line [1,3]
1. lambda/4 equivalent:



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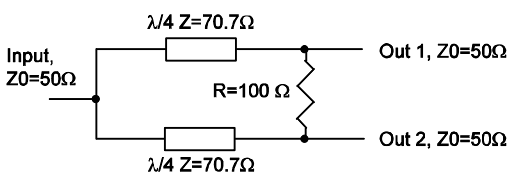
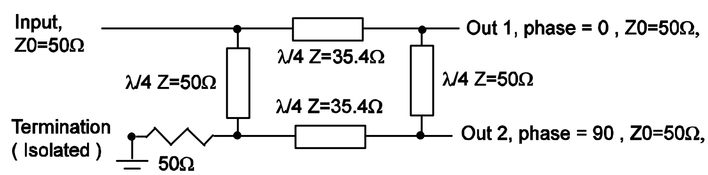
2. Phase Shifting Circuits: Can design lumped element phase shifting circuits which approximate any desired line length

B. Wilkinson Splitter: Combines or splits power evenly between two ports [1,2]



C. Branch Line Quadrature Hybrid: Combines or splits power with 90 degree phase shift [2]:



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6. *ARRL Handbook for Radio Amateurs*, ARRL, any recent year.
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Software:
Appcad (transmission line design and other features) free from Agilent Technologies (www.hp.woodshot.com)
Smith Chart 2.0 (www.rfglobalnet.com/Downloads) from Prof. Prof. Fritz Dellsperger

Multiple commercial software packages for RF design are available including those from Ansoft (www.ansoft.com), Agilent (eesof.tm.agilent.com), Applied Wave Research (awr.com), among others.